Paints, Paper, and Programs: First Steps Toward the Computational Sketchbook

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ABSTRACT

This paper describes what we believe to be important initial steps toward realizing a novel computational medium that combines elements of programming, painting, and papercrafts. Briefly, this genre of *paper computing* allows a user to create functional computational artifacts on painted paper substrates. We introduce a construction kit for paper computing that consists of computational elements—microcontrollers, sensors, actuators, and power sources—that are held on paper surfaces by magnetic paint and magnets. Conductive paint applied to these surfaces takes on the role of "wires", connecting the computational elements to one another. These elements can be moved around and from surface to surface, much like magnets on a refrigerator, and the overall result is a tangible medium in which painting, programming, and the affordances of paper blend together. In addition to introducing the kit, we describe example constructions and discuss a variety of potential applications, design projects, and issues for continued research.

Keywords

Paper computing, conductive paint, magnetic paint, papercrafts, construction kit.

INTRODUCTION: BLENDING BITS WITH PAPER

Over the past thirty years or so—since the advent of interactive computing—it has been a repeated observation that the medium of paper and the medium of computation, despite some overlap in their day-to-day functions, nonetheless present distinct affordances to users. Working with paper allows for a certain degree of fluidity of activity—carrying informal notebooks, sketching on napkins, posting drawings on a wall, filling boxes with index cards, and so forth—that somehow seems to elude computational media. Mackay *et al.* [12] list a few of the salient advantages of paper as a creative medium:

> "Researchers have shown that paper has many benefits difficult to replace with standard monitor/keyboard/mouse interfaces. Paper is easier to read and meets subtle needs for people working collaboratively. It is also lightweight, inexpensive, ubiquitous, and easy to use."

These authors could have mentioned still other possibilities of paper—that (e.g.) it can be cut into party decorations, folded into origami and paper dolls, made to move in popup cards, and so forth—all the while continuing to act as a surface for information display.

In response to the distinct but complementary features of these two media, there have been repeated, creative, and often promising attempts to bridge the two worlds. Indeed, the just-quoted article by Mackay *et al.* is one such project, describing several prototypes of laboratory notebooks that combine PDAs and graphics tablets with paper notebooks to permit users to (e.g.) annotate, store, and evaluate their handwritten paper notes with computational tools. Still other efforts have employed alternative types of integration: the HyperGami and Popup Workshop programs [7,10], for example, permit users to design paper polyhedra and popup cards (respectively) on the computer screen, print out templates on a color printer, and assemble a tangible folded object. In work more closely related to issues we will discuss here, Coelho *et al.* explored "pulp-based computing"—embedding electronics into lovely hand-made papers [4]—and the group Graffiti Research Labs conducted a variety of playful experiments with conductive paints and paper [9]. Meanwhile, innovations such as electronic paper [5] and e-ink [6] have begun to provide computational screens with some of the physical characteristics—at least the reflectance and (to some extent) flexibility of paper.

This article describes what we believe to be important initial steps toward yet another means of bridging the worlds of computation and paper: a construction kit for paper computing that enables people to—relatively quickly and easily—meld the creative affordances of paper and computation to make interactive paintings and sketches. The kit consists of paper-mounted electronic and computational modules that can be directly placed onto

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painted paper surfaces where they can (e.g.) turn on lights, activate motors, and make sounds.

Before describing this notion, and our initial implementation, in greater detail, it may be useful to view an example of what paper computing looks like, as shown in Figures 1 and 2. Figure 1 shows a paper surface that has been treated, by hand, with a layer of magnetic paint on its reverse side; on the front, the paper has been decorated (using a paintbrush) with both conductive and regular (nonconductive) paints. The conductive paint, in light gray, acts as "wires" between the various computational elements that have been placed onto the paper; Figure 1 includes a microcontroller, power source, speaker, switch, and several small LEDs. The program within the microcontroller (the larger circular element toward the center of the figure) directs the behavior of the decoration on the paper: in the figure, the user is causing several lights to shine, and the speaker to emit sound, by touching a skin-conductance sensor that is painted directly onto the page.

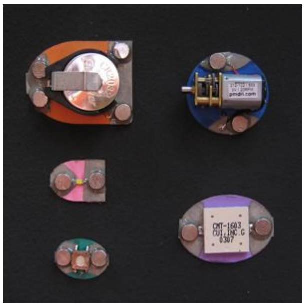
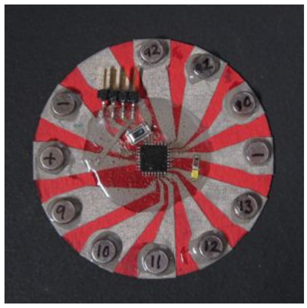
In short, then, what we have produced in Figure 1 is a little running program that produces effects on a paper surface rather than on a screen. In Figure 2, we see the larger context in which this program has been produced, as the sketchbook page on which it sits is turned.

The remainder of this article is devoted to exploring the possibilities of this style of paper computing in greater detail. In the following (second) section, we provide an overview of the implementation of our first construction kit prototype; the third section places this prototype and our example constructions within a larger history of "paper engineering", and uses our kit and examples as a springboard for imagining innovative designs and research projects in engineering education, the arts, and in information displays. The final section briefly discusses some of the challenges of working in this medium.


Figures 1 (left) and 2 (right). A paper computing project—an interactive "botanical design"—in which a microcontroller is used to control light and sound in response to a user's touch. A video can be found at the following URL: www.youtube.com/watch?v=-LyKmaz_3uI

A PROTOTYPE PAPER COMPUTING KIT

The system with which we have built our prototypes is, in effect, a construction kit that enables a user to paint computational and electrical sketches.

Figures 3 (left) and 4 (right). Components of our paper computing kit. Left: clockwise from upper left: a battery, motor, piezo speaker, switch, and LED. Right: a paper-based microcontroller; a paper Arduino.

Our kit currently consists of the paper-mounted modules shown in Figures 3 and 4: a battery, a small geared motor, a piezoelectric speaker, several switches, several LEDs, and a microcontroller, but this could be extended in ways that we will shortly discuss. Each component is mounted on a uniquely colored paper: LEDs are pink, switches are green, batteries are orange, and so on. The polarity of pieces like batteries and LEDs is indicated by the shapes of the boards—flat sides are negative and round sides are positive.

Each component of the kit shown in Figures 3-4 is a small paper circuit board. To build these boards, we employed a technique we developed for creating fabric PCBs [2], attaching an adhesive-backed conductive fabric to paper cutouts. The fabric is wrapped around the edge of each paper cutout so that electrically connected, exposed areas of fabric are on the top and bottom of each module. Once the conductive fabric is attached to paper, electronic components are soldered to it in the same way they would be soldered to a traditional PCB. A component is soldered to the top of each board and electrical contact with painted circuitry is made when an exposed area of conductive fabric on the bottom of the board touches an area of conductive paint. Magnets are glued onto the tops of the boards so that the pieces will snap onto magnetic surfaces and maintain robust physical and electrical contacts.

The final components of the kit are magnetic and conductive paints [8]. We are using a water-based conductive paint, CuPro-Cote, that is easy to employ and relatively non-toxic. We are also using a water-based magnetic paint. Both behave essentially like traditional water-based acrylic paint and can be handled in much the same way.

A crucial aspect of this construction kit is that it is entirely end-user-programmable. Our microcontroller module—this board contains an Atmega168 microcontroller, a reset switch and indicator LED—functions as a paper-based Arduino that can be programmed using the popular open-source Arduino IDE [1]. To program a construction, a user attaches one end of a programming device to the 4-pin header on the paper module and the other end to a USB port on her computer. (This connection can be seen in Figure 6, below.) She can then write Arduino programs and download them to the microcontroller module with a click of a button.

Our paper computing kit is similar in this way to the LilyPad Arduino kit that we developed for working with computation and textiles, and a more thorough description of the programming process may be found in [3]. For our purposes here, the key point is simply that paper computing is not solely a matter of equipping paper forms with pre-written programs (though that might also be done), but allows for user participation in the creation of the programs themselves.

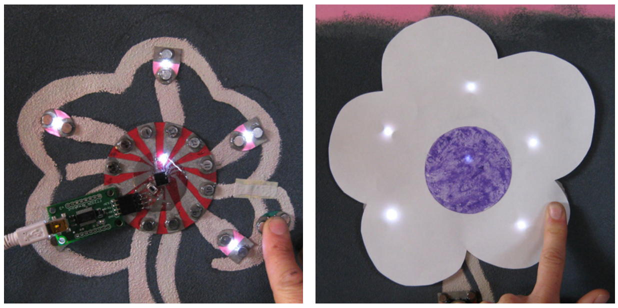
PAPER COMPUTING: A DESIGN LANDSCAPE

The previous section provided a brief description of the basic components for creating paper computing artifacts. In this section we build on this still-very-new foundation to suggest a wealth of potential applications, design projects, and research issues to explore. This section can be read, then, as a first glimpse at what could emerge as an expansive, and creative, design space bridging the worlds of paper and computing.

Interactive paintings. Figures 1 and 2 hint at the ways in which electronics, computation, and painting can be combined to create artifacts that don't look or feel like traditional technological devices. Being able to paint circuits opens up new aesthetic and expressive possibilities for electrical engineering and, we believe, has the potential to make engineering accessible and appealing to new audiences. It is also worth noting that constructions need not be computational; it is possible to paint out simple circuits. Figure 5, for example, shows a close-up of a painting that includes only a battery and motor.

Figure 5. A non-computational painting that includes a motor, with an attached paper spiral, and battery.

Magnetic paper stacks. Figures 6 and 7 show a sample project that illustrates one of the ways in which paper computing dovetails with the techniques of papercraft construction. In Figure 6, conductive paint has been applied (in light gray) to a paper surface to produce a circuit pattern. That pattern is then employed in Figure 7 as follows: a microcontroller controls a switch (which a user is pressing in the figures), and several LEDs that are arranged in a flower pattern. What is interesting here is that the microcontroller has been hidden behind paper cutouts (the white flower and purple disk in Figure 7) that have themselves been treated with magnetic paint and placed over the component. Thus, a single interactive painting could take on different personalities when different cutout "costumes" are placed over it. Additionally, cutouts containing RFID tags, magnets, or other elements could influence the behavior of constructions more directly.



Figures 6 (left) and 7 (right). A paper computing project in which the circuitry is covered by 2 additional magnetic paper layers visible in Figure 7: a flower-shaped cutout and a circular purple cutout. Also visible in Figure 6 is the programming attachment.

Paper engineering. There is a long and beautiful history of artistry that makes use of the mobility of paper. The most prominent type of this work is in the realm of popup cards and books, where the motion of the paper is imparted by the opening or closing of the object. More generally, work in this area is known as paper engineering by many of its practitioners, involving as it does additional elements such as paper tabs that can be pulled to move or animate figures on a page; paper wheels (or volvelles) that can be turned about on their axes; flaps that open and close; and many more. [Cf. [10], chapters 3-4; and [11]] Because our paper computing components include a motor actuator (shown in Figure 3), it should be possible to experiment with paper engineering structures that are endowed with computationally controlled behaviors. Figure 5 shows a simple example of this integration: a paper spiral is attached to the motor and this spins across the page when the motor is triggered. But we believe this only hints at the possibilities in this realm. A popup form might blossom in response to the placement of a user's hands, or a volvelle might turn in response to a touch sensor. The blending of (new) paper computing and (venerable) paper engineering offers remarkable potential for artistic symbiosis.

Animated paper sculpture. Although it would be difficult to perform full-fledged origami folding on a treated paper surface, it should be feasible to treat regions of the paper after it has been folded, and to attach components to origami forms or paper sculptures. As a result, one could imagine animating paper sculptural forms—to show moving wings, legs, or joints of a paper animal, or to animate a transformation such as the opening of an accordion fold.

Games. There is a natural extension of paper computing to the development of games and interactive activities in which the "game board" is painted onto a paper surface, and computational pieces are moved about on the board. The possibilities here range from employing paper computing to (say) illustrate moves in traditional games like checkers, to the creation of entirely new games and pastimes.

Specialty papers, paints, and other materials. A rich assortment of materials could be fruitfully combined with paper computing, including: diffraction gratings, polarized films, mirrored surfaces, thermochromic inks, electroluminescent inks, e-ink, graphite pencil lead, and the like. Electroluminescent inks—just to take this one example—offer the possibility of lighting up lines or regions under program control (in contrast to our current LED actuators, which can only illuminate a point region).

Prototyping tangible user interfaces. Paper constructions need not be stand-alone artifacts; they can also function as interfaces to computers or other more sophisticated computational devices. With the addition of a communication piece—like the USB programming attachment mentioned earlier or any common wireless module—it's possible to use our kit to quickly "sketch" or paint functioning tangible user interfaces on paper.

Educational research. Finally, it should be mentioned that paper computing offers a very real possibility of creating innovative interactive textbooks for the teaching of material such as computer programming, algorithms, or discrete mathematics. For example, a dynamic display could illustrate the behavior of a cellular automaton; the movement of a random walker on a plane; the locus of control in a deterministic finite automaton; the properties of a Markov chain; and so forth. In this sense, paper computing as a medium may come to enrich the practice of the original computing tradition from which it has emerged.

CHALLENGES

Along with a plethora of creative possibilities, paper computing presents a unique set of design challenges, which this section will briefly discuss. First, the materials that we are using have specific physical limitations. In particular, commercially available conductive paints take time—usually 10-15 minutes—to dry, and a circuit often requires two coats of paint. While it is quite satisfying to literally sketch a functional prototype on paper, one would like to be able to realize ideas as quickly as one could sketch. Furthermore, the paint we are using—even when optimally applied—has a non-trivial electrical resistance; it has a surface resistivity of 5 Ωs/square. In practice this means that one has to factor current draw, voltage drop, and communication speed into designs more than usual.

Perhaps more interesting than these physical limitations however are medium-specific design challenges and questions that our experiences have brought to light. For example, how does a user know where to place magnetic modules on a sketch to get the sketch to function properly? Our current microcontroller module is a sphere—a symmetrical shape that has no natural orientation—and we found that it was easy to place this module upside down or sideways on a sketch. Could the right module design naturally enforce important placement constraints? Another group of questions arise from the fact that sketches necessarily include areas of exposed conductive paint. This means that it's easy to create not only non-functioning configurations, but also harmful ones by, for example, placing a power-supply module backwards across power and ground. Can (and should) the kit be designed to ensure that users never make harmful constructions?

In short, we are in the early stages of exploring a new medium that presents a rich set of new design challenges and opportunities.

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